DIVERGING DIAMOND INTERCHANGES

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American Society of Highway Engineers
2010 National Conference | June 9-13, 2010

Zig? Zag? What!....
DIVERGING DIAMONDS

2010 ASHE National Conference

June 10, 2010

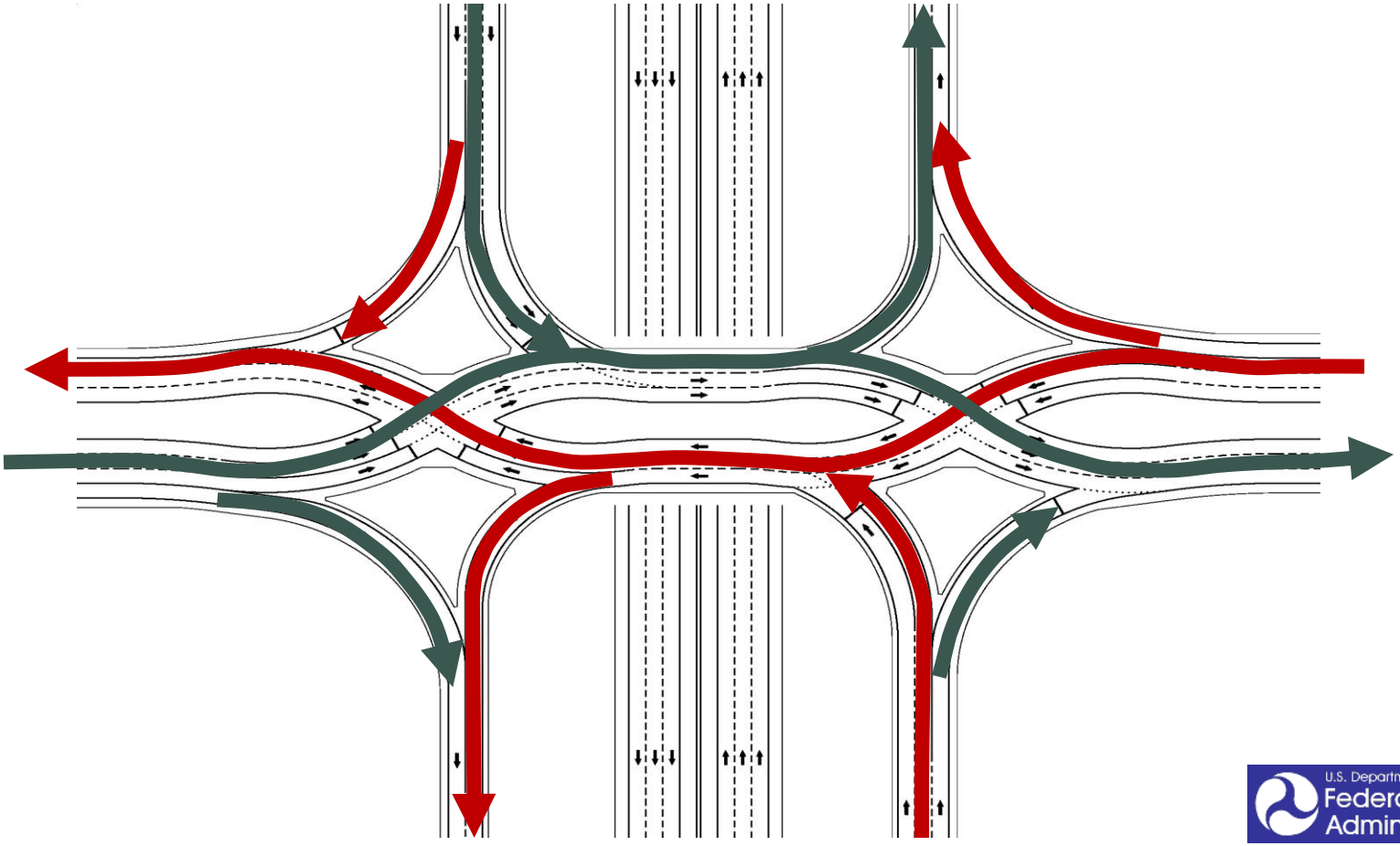
Carol Callan-Ramler, P.E.

Kentucky Transportation Cabinet, District 6

What is a Diverging Diamond Interchange (DDI)?

- A non-traditional design to accommodate left-turning movements at signalized, grade separated interchanges while eliminating the need for left-turn phasing of the traffic signals.
- Also known as a Double Crossover Diamond (DCD)

What is a DDI? Continued



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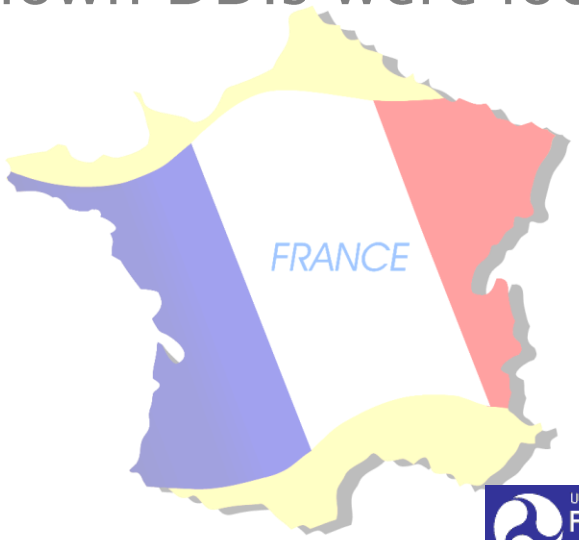
From Where did DDI's Originate?

- The DDI originated in France in the 1970's
- Until recently, the only known DDIs were located in France:
  - Versailles
  - Le Perreux sur Marne
  - Seclin



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A13 & RD182
Versailles, France

Only 11 light injury crashes reported in 5 years compared to an average of 23 fatal/injury crashes of a typical DI in the USA

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D45 & A4
Le Perreux sur Marne, France

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A1 & D549
Seclin, France

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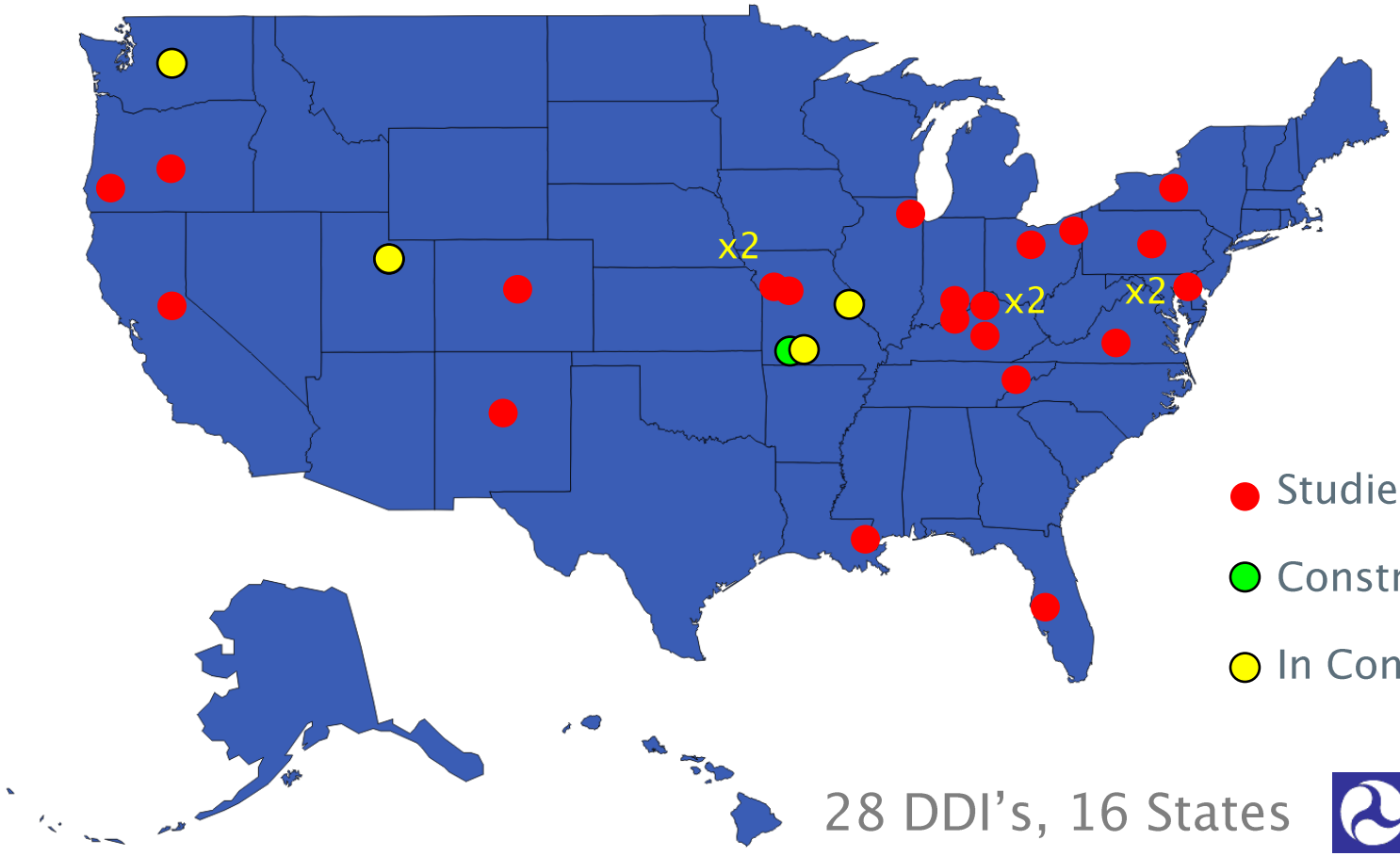
Diverging Diamonds Around the USA



28 DDI's, 16 States

U.S. Department of Transportation
Federal Highway Administration

DDI's in Missouri

- Studied
- Constructed

WHY a Diverging Diamond?

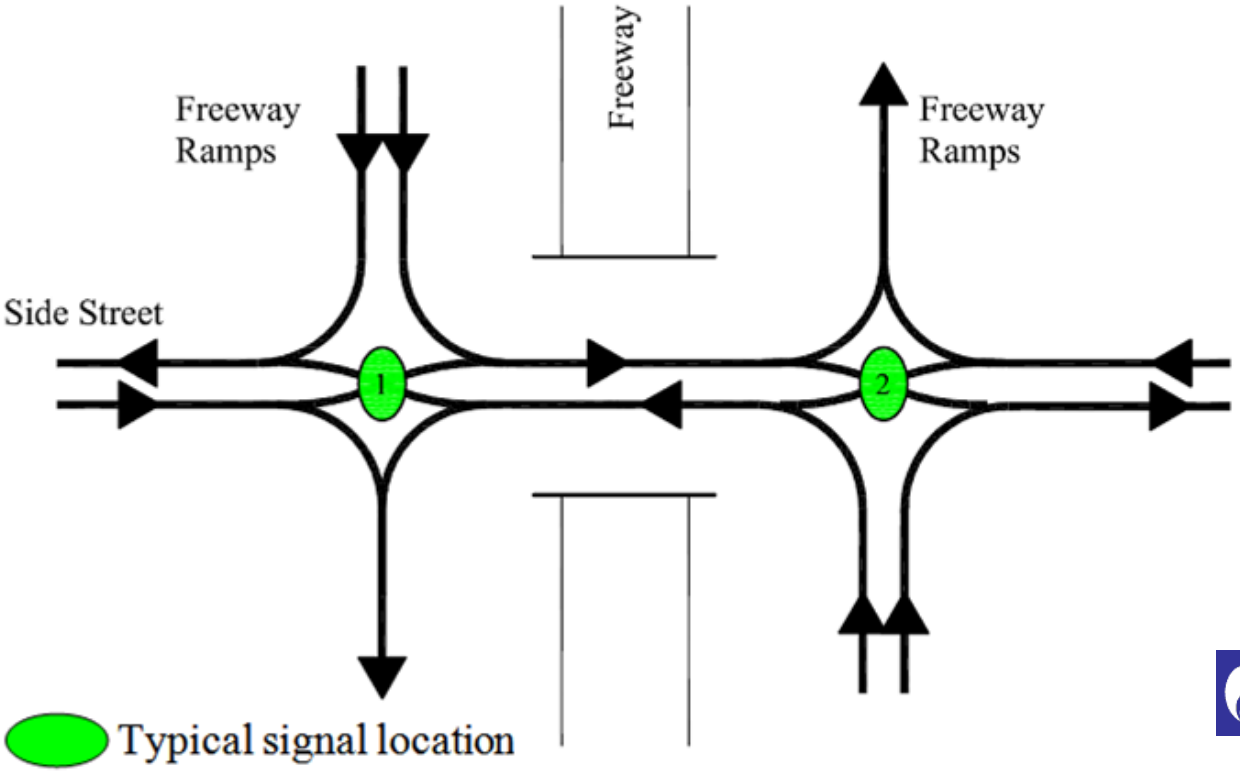
- Improved Operations/Reduced Congestion
- Theoretical Safety Improvements
- Project Costs

WHY a Diverging Diamond?

- **Improved Operations/Reduced Congestion**
- Theoretical Safety Improvements
- Project Costs

WHY a Diverging Diamond? *Operations*

- Improved operational benefits with 2-phase signal operation since left-turn phase is eliminated



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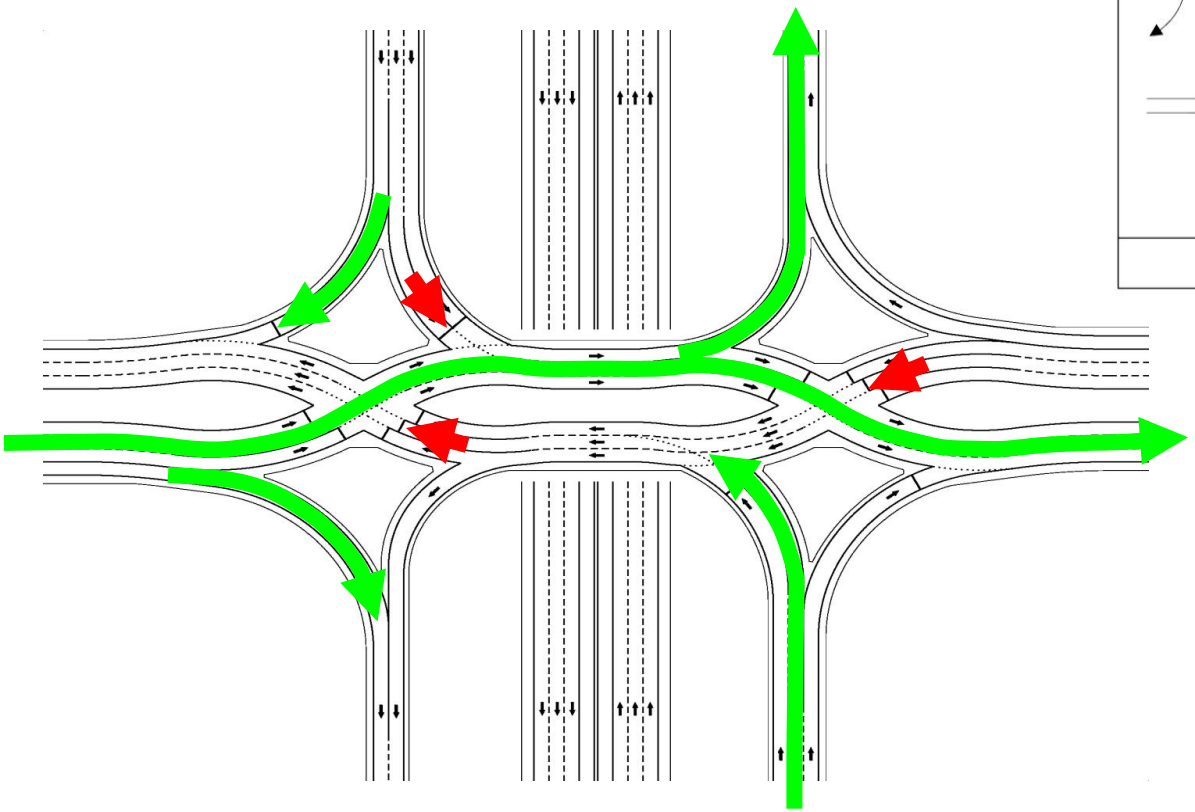
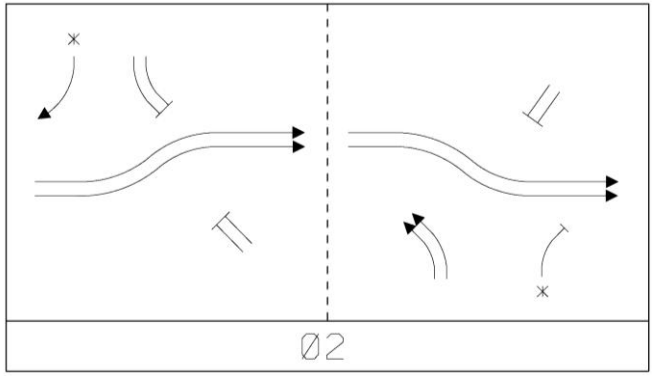
WHY a Diverging Diamond? *Operations*

Signal Phasing





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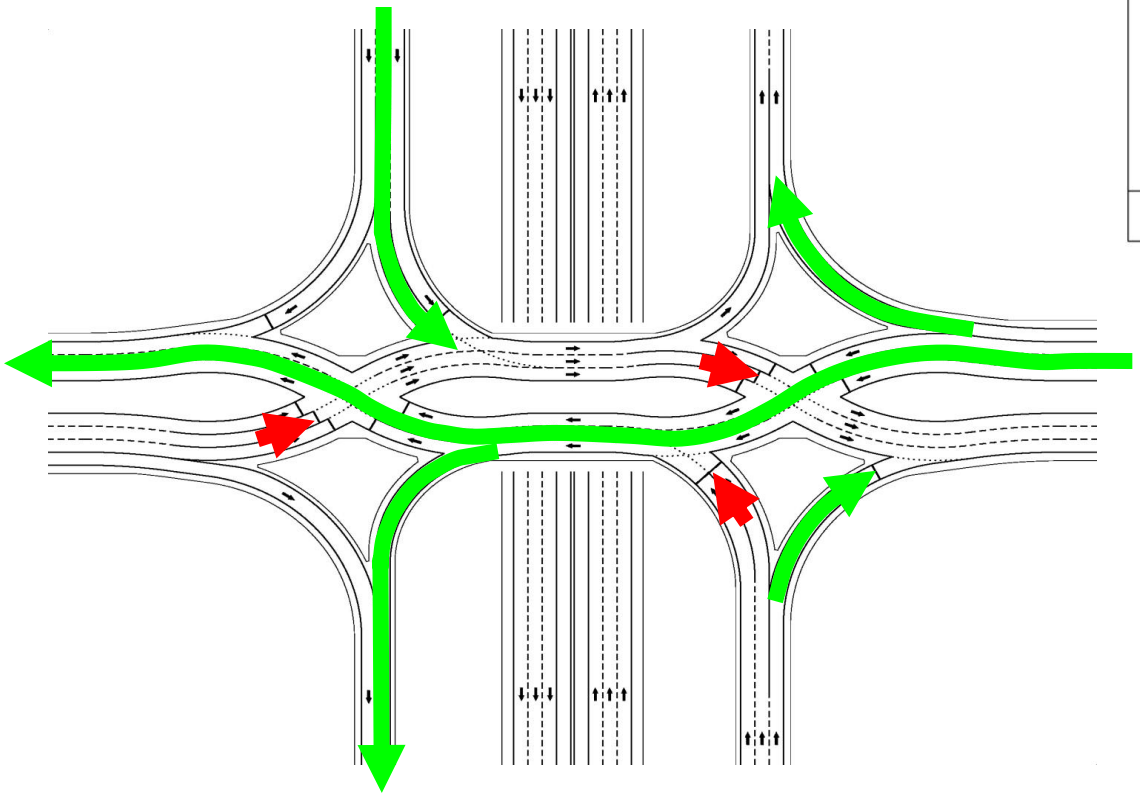
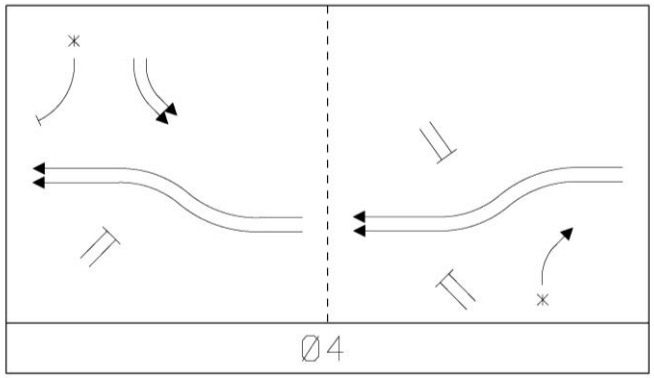
WHY a Diverging Diamond? *Operations*

Signal Phasing, Continued





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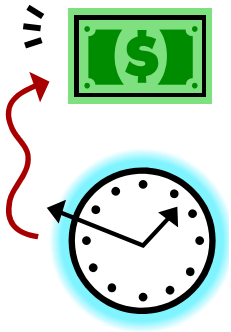
WHY a Diverging Diamond? *Operational Benefits*

- Research has shown that compared to a traditional diamond interchange, the DDI:
  - Reduces intersection delay by 15% to 60%
  - Increases throughput by 10% to 30%
  - Increases overall capacity by 15% to 25%



- A DDI accommodates heavy left turn volumes onto ramps and from off-ramps
- A DDI accommodates moderate or unbalanced through volumes

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WHY a Diverging Diamond? *Operational Benefits*

- A DDI can combine lane assignments for the left-turn and through movements on/below a bridge structure and permits a more narrow footprint.
- An on-ramp left-turning volume > 300 v/h/l
- An off-ramp left-turning volume < 700 v/h/l
- A mainline through volume in both directions < 650 v/h/l

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WHY a Diverging Diamond? *Operational Benefits*

- An existing bridge deck with limited width, where bridge expansion is unfeasible or prohibitively expensive
- Intuitively, reduction in congestion is a reduction in air emissions.
  - To date, not aware of any analysis or research to substantiate this claim.

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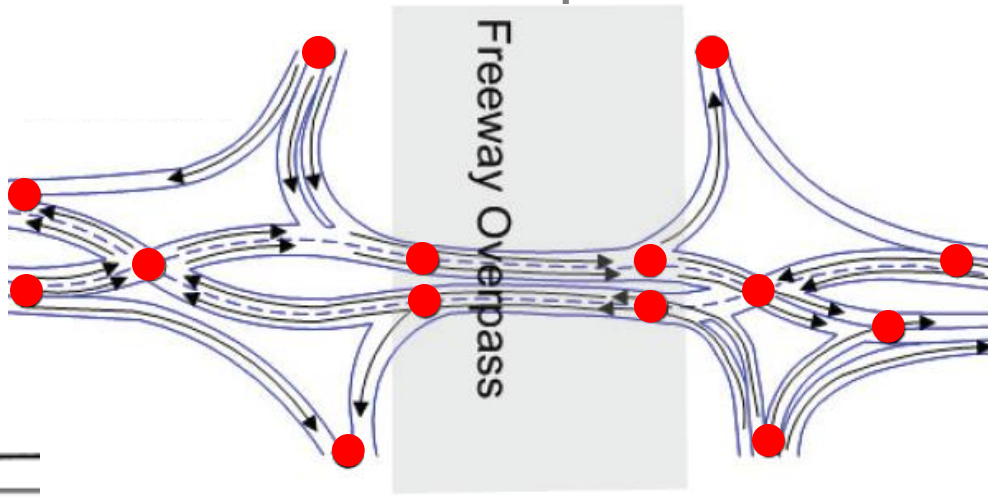
WHY a Diverging Diamond?

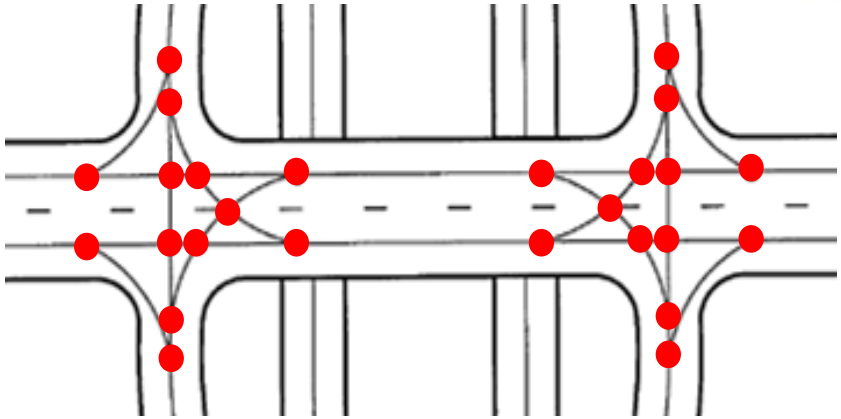
- Improved Operations/Reduced Congestion
- **Theoretical Safety Improvements**
- Project Costs

WHY a Diverging Diamond? *Safety*

- Theoretical safety benefit from reduction in potential vehicle-to-vehicle conflict points

  - DDI: 14 Conflict Points





  - Traditional Diamond Interchange: 26 Conflict Points
  - Single Point Urban Interchange: 18 Conflict Points

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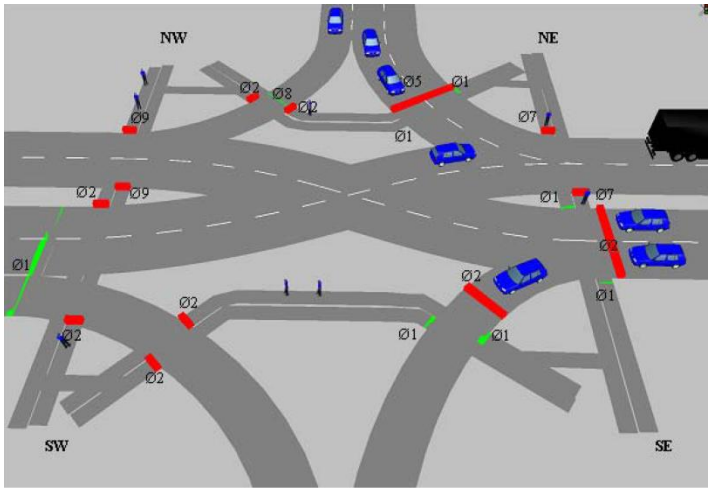
WHY a Diverging Diamond? *Safety*

- Theoretical pedestrian safety improvement with multi-stage crossing as pedestrians only cross one direction of traffic at a time.
- Curvature reduces vehicle speeds through intersections



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WHY a Diverging Diamond?

- Improved Operations/Reduced Congestion
- Theoretical Safety Improvements
- **Project Costs**

WHY a Diverging Diamond? *Cost*

- Potential for reduction of infrastructure costs through reduction of needed lanes and underpass/overpass bridge width
- Potential reduction of right of way costs
- Potential reduction of construction time

WHY a Diverging Diamond? *Cost*

- MoDOT's Experience with Cost:
  I-435 & Front Street
  Kansas City, MO

  Gateway to Northeast Industrial District

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WHY a Diverging Diamond? *Cost*

I-435 & Front Street Alternatives: TUDI vs. DDI

- Estimated Costs

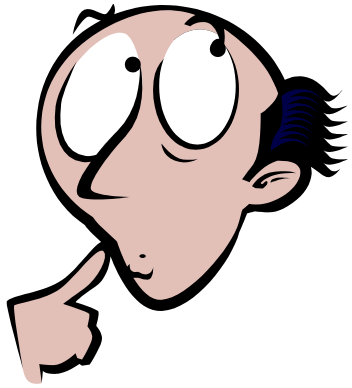
	TUDI	DDI
Construction	$ 6,866,000	$ 4,918,000
Right of Way	$ 3,868,000	$ 1,445,000
Utilities	$ 600,000	$ 391,000
Total Costs	**$11,354,000**	**$ 6,754,000**

- Operations
  - TUDI – 8 lanes, LOS C–F, Capacity @ 95%
  - DDI – 4 lanes, LOS A–C, Capacity @ 60%
- Safety
  - TUDI – 45 Conflict Points
  - DDI – 21 Conflict Points

TUDI – Tight Urban Diamond

Why Not Select a Diverging Diamond?

- The DDI is a new concept to drivers in the US.
- The crossover maneuver is not intuitive because drivers travel on the opposite side of the road.
- Concern that driver unfamiliarity will result in an increase in crashes.
- Pedestrians might have to cross free-flowing ramps.



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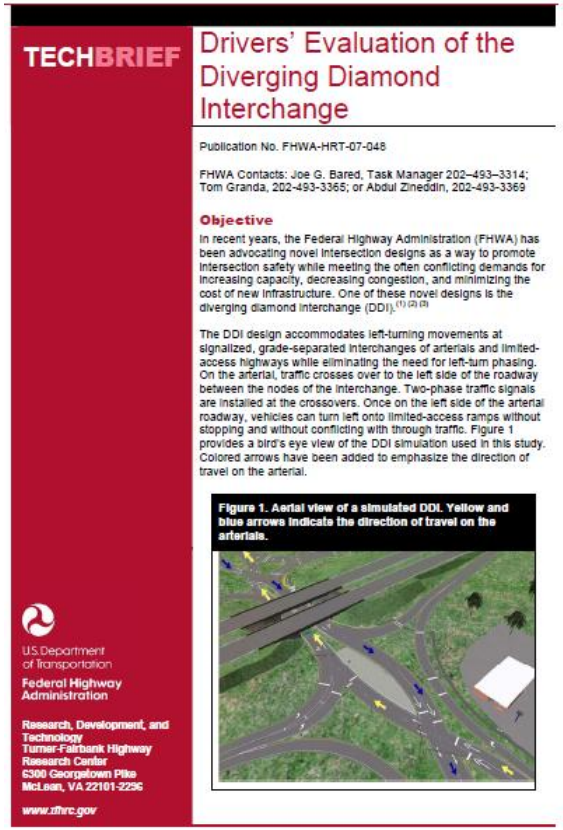
FHWA Human Factors Driver Simulation Study

- Simulation of I-435 & Front Street DDI in Highway Driving Simulator at Turner-Fairbank Highway Research Center
- Three simulated interchanges – DDI, DDI (Mod), and Diamond
- 74 Drivers (Balance male/female & over/under 65)
- Results published in FHWA Tech Brief (www.tfhrc.gov)



TECHBRIEF

Drivers' Evaluation of the Diverging Diamond Interchange

Publication No. FHWA-HRT-07-048

FHWA Contacts: Joe G. Bared, Task Manager 202–493–3314; Tom Granda, 202-493-3365; or Abdul Zineddin, 202-493-3369

Objective

In recent years, the Federal Highway Administration (FHWA) has been advocating novel intersection designs as a way to promote intersection safety while meeting the often conflicting demands for increasing capacity, decreasing congestion, and minimizing the cost of new infrastructure. One of these novel designs is the diverging diamond interchange (DDI).[1] [2] [3]

The DDI design accommodates left-turning movements at signalized, grade-separated interchanges of arterials and limited-access highways while eliminating the need for left-turn phasing. On the arterial, traffic crosses over to the left side of the roadway between the nodes of the interchange. Two-phase traffic signals are installed at the crossovers. Once on the left side of the arterial roadway, vehicles can turn left onto limited-access ramps without stopping and without conflicting with through traffic. Figure 1 provides a bird's eye view of the DDI simulation used in this study. Colored arrows have been added to emphasize the direction of travel on the arterial.

Figure 1. Aerial view of a simulated DDI. Yellow and blue arrows indicate the direction of travel on the arterials.

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Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

www.tfhrc.gov

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FHWA Driver Simulation Analysis
I-435 & Front Street, Kansas, MO

FHWA Driver Simulation Analysis

I-435 & Front Street, Kansas, MO

Study MOEs and Results

- Wrong-way Violations
  - No violations at crossover (1041 opportunities)
- Navigation Errors
  - Incorrect path on only 2.3% of opportunities
- Red-light Violations
  - Similar frequency although rare, but more violation opportunities with conventional diamond
- Speed @ Crossover
  - DDI – avg. 24 mph
  - Diamond – avg. 34 mph

FHWA Driver Simulation Analysis
I-435 & Front Street, Kansas, MO

Simulation Analysis affected sign selection:

FHWA Driver Simulation Analysis

I-435 & Front Street, Kansas, MO

- The safety benefit combined with predicted operational benefits and reduced roadway width requirements make the DDI an attractive interchange alternative.

- Simulation Study suggests potential driver confusion not as significant of a concern and is mitigated with proper design (reverse curvature), signing, and markings

MoDOT: Public Response

Missouri DOT Staff Summary: DDI Results from the Right Transportation Solution Survey

http://library.modot.mo.gov/RDT/reports/TRyy1013/orb10005.pdf

- Opened June 2009, survey results received December 2009
- Survey from residents from eight ZIP code areas and mailed a total of 400 Springfield area addresses the survey. A total of 75 responses were received, which is a gross response rate of about 19%.

MoDOT: Public Response

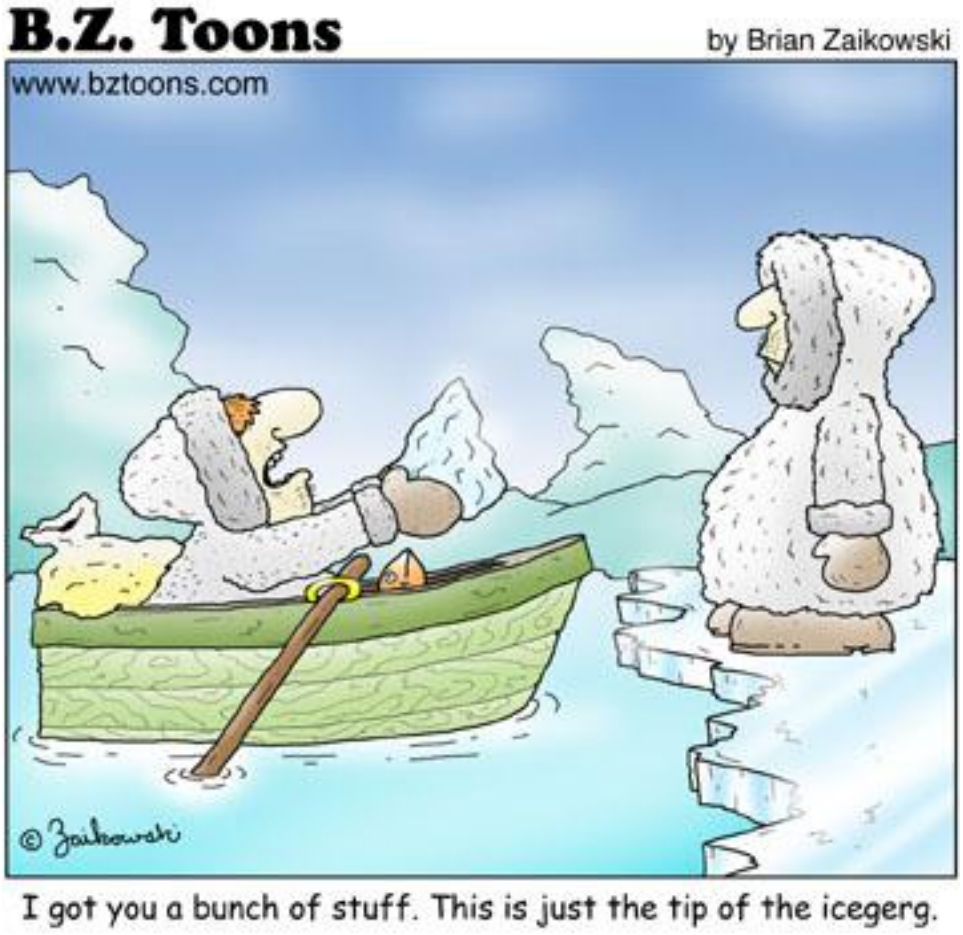
- Most Springfield area residents were very satisfied with the project and generally believe MoDOT provided the right transportation solution (89.4%).

- More than 85% of the respondents were either “very” or “fairly” familiar with the project roadway.

MoDOT: Public Response

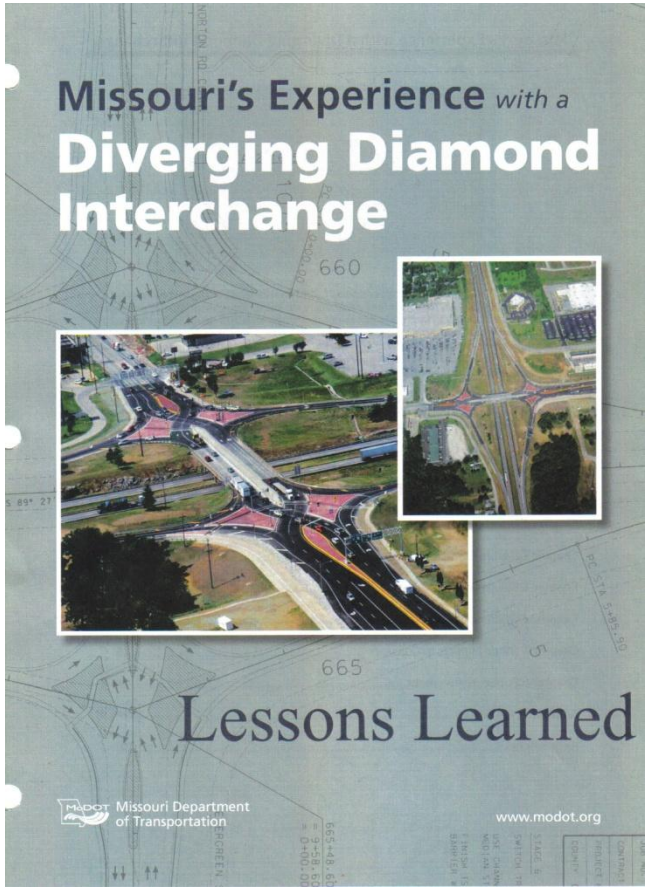
- The overwhelming majority of the respondents thought the project:
  - made the roadway safer (96.7%)
  - more convenient (95.1%)
  - less congested (95.2%)
  - easier to drive (86.9%)
  - better marked (89.8%)

MoDOT's Lessons Learned



MoDOT's Lessons Learned

- Comprehensive Report: covering intersection spacing, horizontal geometry, sight distance, signals, striping to maintenance and operations, and public involvement
- http://library.modot.mo.gov/RDT/reports/UnNumbrd/or10021.pdf



MoDOT's Lessons Learned
Spacing of Intersections

- Exercise caution of other existing signalized intersections that might be too close to the DDI such that the efficient operations of the DDI will be impaired due to the small space for necessary queuing.

MoDOT's Lessons Learned
Horizontal Geometry

- Design Speed
  - Major controlling element of a DDI is the horizontal geometrics which can act as traffic calming.
  - Regular passenger vehicles: 20-30 mph, to date 25 mph is maximum used
  - WB 67s:
    - Through movement: 20 mph
    - Ramp movement: 15 mph

MoDOT's Lessons Learned
Horizontal Geometry

- MoDOT experience: cross roads' design with both with reverse super and normal crown
- The design of the horizontal geometrics for each crossover is site specific.
- Center of crossover offset and skewed from centerline of cross route

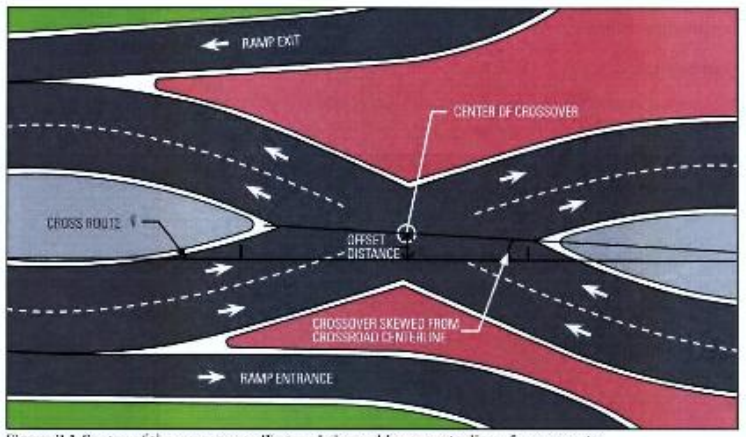


Figure 2.1 Center of the crossover offset and skewed from centerline of cross route

MoDOT's Lessons Learned
Horizontal Geometry

- Space for vehicular storage
  - Between Crossovers
  - Ramps
  - Combination
- May shift location of center of crossover away from ramp baseline termini.

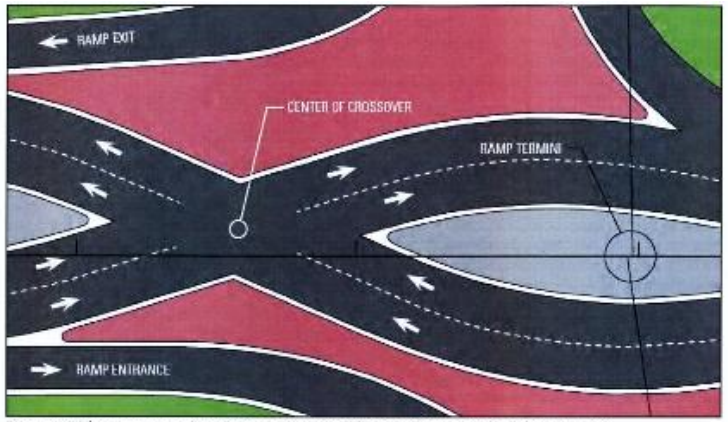


Figure 2.2 The crossover placed approximately 150' away from ramp baseline termini

MoDOT's Lessons Learned
Horizontal Geometry

Crossing Angle:

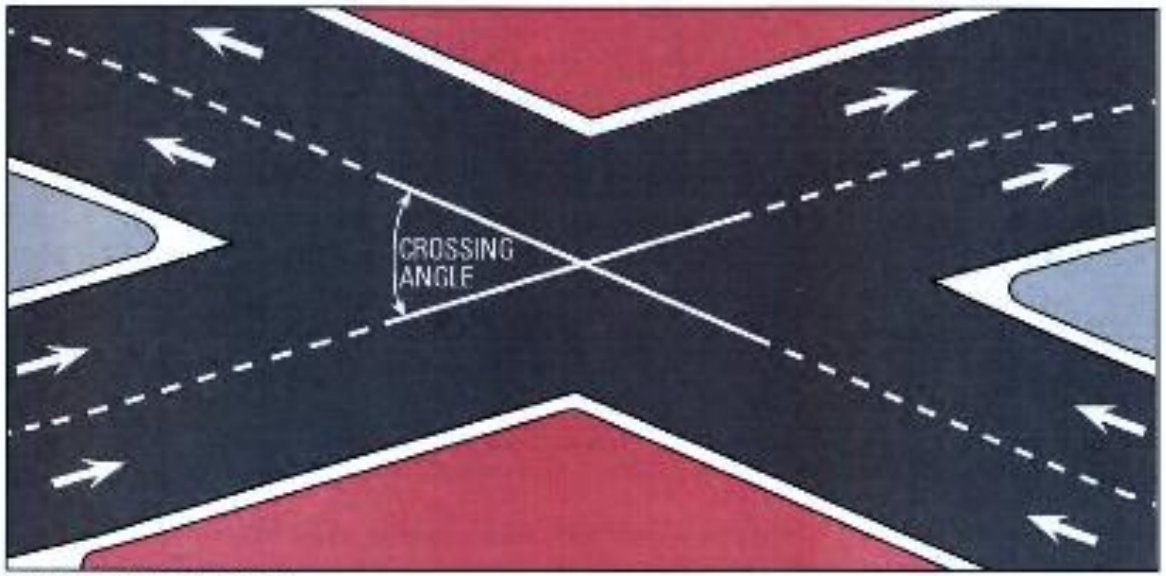


Figure 2.3 Crossing Angle

MoDOT's Lessons Learned
Horizontal Geometry

Crossing Angle:

- Minimizing likelihood of driver error into opposing traffic – the greater the angle the more "normal"
- The greater the angle, minimizes the distance across the intersection and minimizes the exposure a vehicle has to opposing traffic but does increase the DDI footprint
- Greater crossing angles can increase the potential for driver discomfort and potentially aid traffic calming.

MoDOT's Lessons Learned
Horizontal Geometry

Crossing Angle:

- Greater crossing angles can increase the potential for driver discomfort and potentially aid traffic calming.
  - Caution: consider safety of vehicles with higher centers of gravity. Sharp reverse curves have the potential for overturning.
- MoDOT crossing angles range from 40-50 degrees; use the largest possible

Figure 2.3 Crossing Angle

MoDOT's Lessons Learned
Horizontal Geometry

Tangent Length

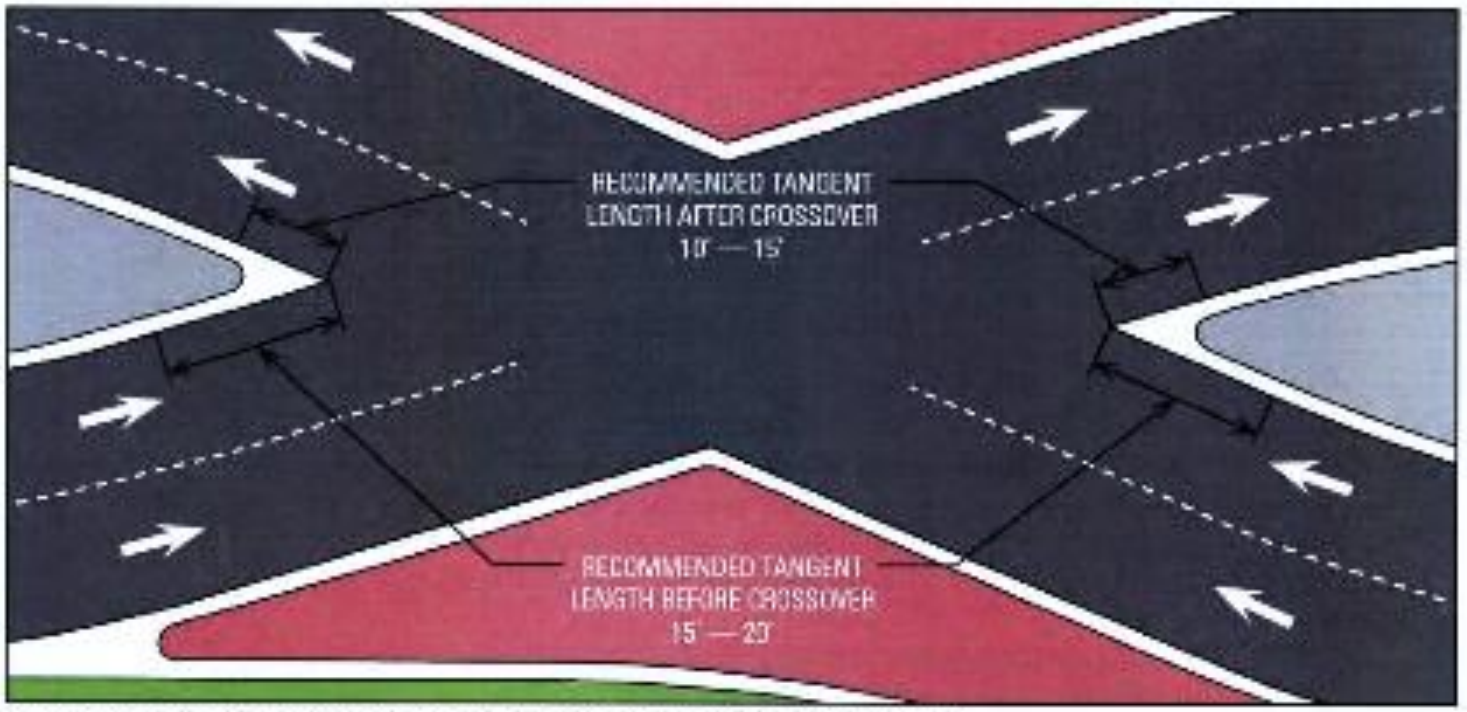


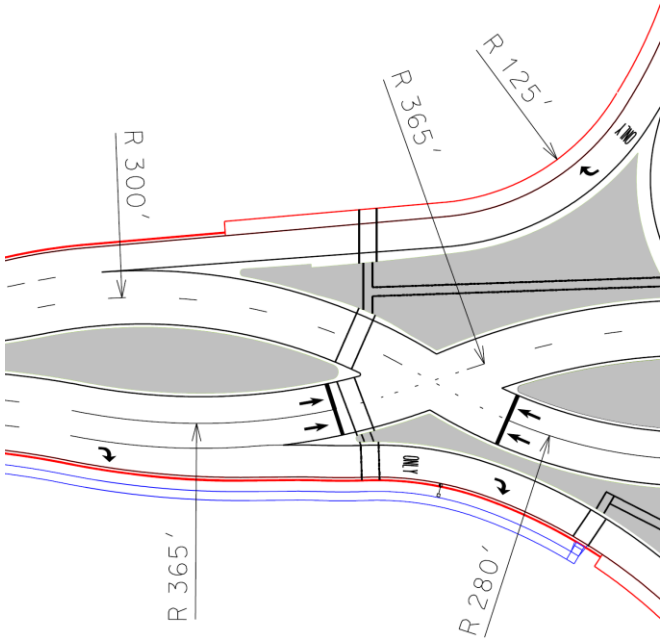
Figure 2.5 Recommended tangent length before and after crossover

MoDOT's Lessons Learned
Horizontal Geometry

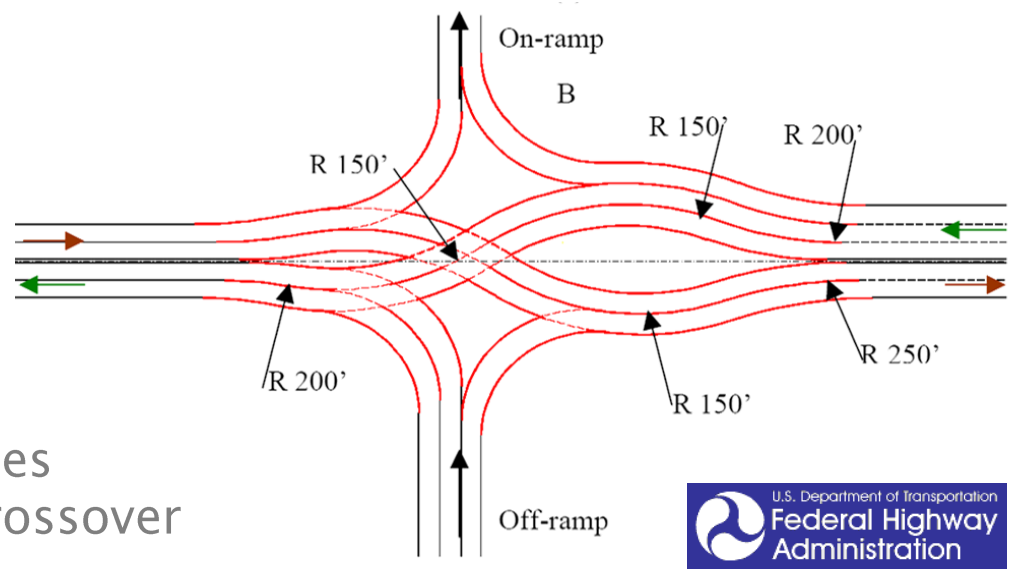
- Cross Slope
  - Springfield used normal crown (drained outward); St. Louis used 4% reverse super (drained inward – put in more drainage inlets)
- Curve Radii:
  - Start with 200' radius along the inner edge of pavement both before and after the crossover and then adjust the radii until optimum design is achieved.
  - Curve radii used in MoDOT DDI designs range generally from 150' to 300'.

MoDOT's Lessons Learned
Horizontal Geometry

- Curve Radii:



Design of I-435 / Front Street:
Larger radii to accommodate high truck/heavy vehicle %



More typical design radii values expected for an urban DDI Crossover

MoDOT's Lessons Learned
Sight Distance

- 2 areas of specific importance to a DDI
  - SD for Vehicles making crossover movements
    - Requires drivers to have an unobstructed view of of the intersection, including any traffic control devices, and sufficient length along the cross route to permit the driver to anticipate and avoid potential collisions. Follow AASHTO Green book.

MoDOT's Lessons Learned
Sight Distance

- Sight lines for vehicles exiting from the limited access highway, single- or multiple-turn lanes.

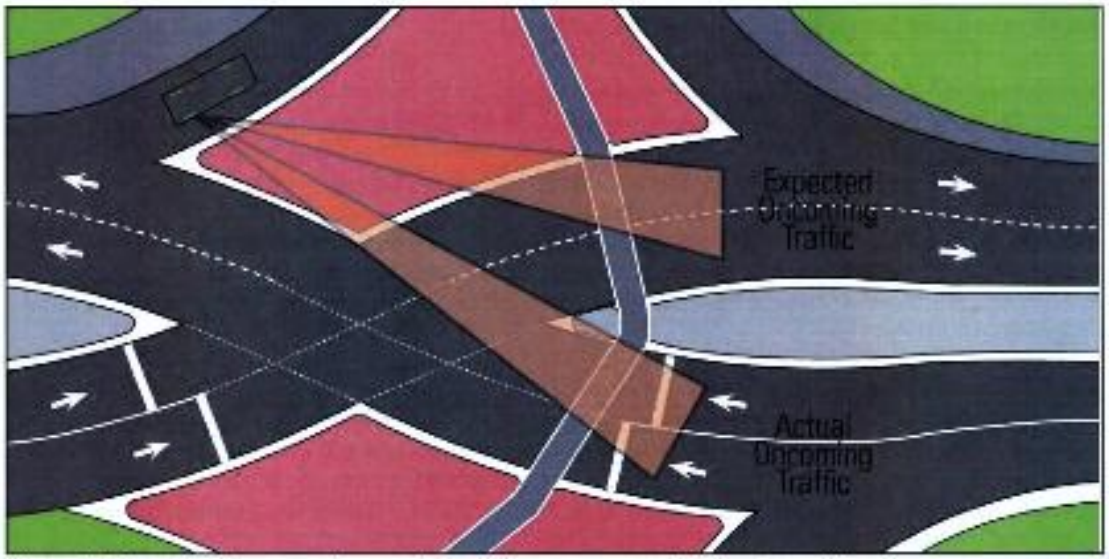


Figure 2.8 Diagram of expected oncoming traffic versus actual oncoming traffic

MoDOT's Lessons Learned
Sight Distance

- This can be minimized by moving the RT turn further from the crossover to increase the amount of SD available & provides more time to realize where oncoming traffic is coming
- Consider channelizing the RT coming off the ramp more so when drivers turn to view the oncoming traffic, it more likely falls in their natural line of sight.

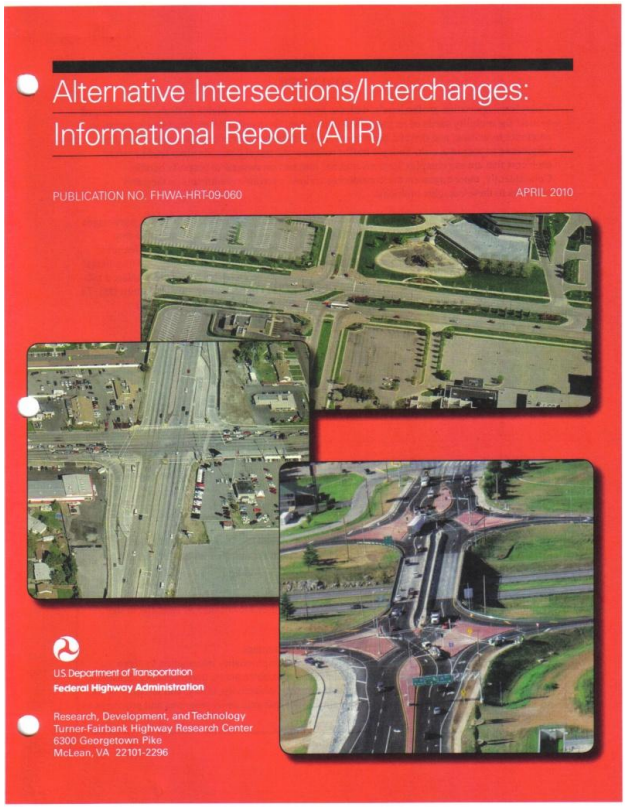
MoDOT's Lessons Learned
Sight Distance

- Median barrier wall height might require tapering near the ends so that SD is increased. Go from 24" to 42"

FHWA/MoDOT's Lessons Learned
Other Recommendations

- Alternative Intersections/ Interchanges: Informational Report
  - References Simulation Study

Publication No. FHWA-HRT-09-060



FHWA/MoDOT's Lessons Learned
Other Recommendations

- Lane width should be around 15 ft.
- Provide adequate lighting
- Consider nearside signals
- Pedestrians at free-turning movements should be evaluated and pedestrian signals may be required.
- Noses of median island should extend beyond the off-ramp terminals to improve channelization & prevent erroneous maneuvers.

FHWA/MoDOT's Lessons Learned
Other Recommendations

- Use of advance signing and guide-sign applications on the exit ramps and on the bridge structure
- Use of advisory speed signs
- Use of skip marks on the left-turn lanes for clear guidance through the crossover area
- Use of overhead signing to clearly communicate lane use and directions
- Use of "Wrong Way"/"Do Not Enter" signs

MoDOT's Lessons Learned
Other Recommendations

- Good resource for bicycle and pedestrian recommendations.
- Signal timing programs such as Synchro are limited with respect to DDIs and signal timing will require field adjustments.

Concluding Remarks

- It's a new tool for our tool box, but it is not a one size fits all. It will not turn out to be the optimal tool on every design situation.
- If designing a DDI, initial design efforts should be from the pavement up, not the pavement down.
- Toss out any thoughts of cookie-cutter design, each roadway element must be considered specifically and also holistically.

Acknowledgments

- Scott Wolf, FHWA
- Joe Bared, FHWA
- Don Saiko, MoDOT
- Various Engineers from Entran, Gresham Smith & Partners and Burgess & Niple

Reference Materials: TECHNICAL

- Joe Bared, FHWA, has developed an inventory of three alternative intersections/interchanges listing sites whereby DOTs and consultants can add their projects to this list.

  http://www.alternativeintersections.com/

- He has provided a list of the latest publication below. The main report has a complete chapter on the double crossover diamond, DCD, and you can get a printed copy of the Tech Brief.

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Reference Materials: TECHNICAL

- Alternative Intersections / Interchanges: Informational Report (online copy only)

  http://www.fhwa.dot.gov/publications/research/safety/09060/

- Double Crossover Diamond Interchange (Tech Brief)

  http://www.fhwa.dot.gov/publications/research/safety/09054/09054.pdf

- Drivers' Evaluation of the Diverging Diamond Interchange

  http://www.fhwa.dot.gov/publications/research/safety/07048/index.cfm

Reference Materials: TECHNICAL

- Displaced Left-Turn Intersection (Tech Brief)

  http://www.fhwa.dot.gov/publications/research/safety/09055/09055.pdf

- Displaced Left-Turn Interchange (Tech Brief)

  http://www.fhwa.dot.gov/publications/research/safety/09056/09056.pdf

- Median U-Turn Intersection (Tech Brief)

  http://www.fhwa.dot.gov/publications/research/safety/09057/09057.pdf

- Quadrant Roadway Intersection (Tech Brief)

  http://www.fhwa.dot.gov/publications/research/safety/09058/09058.pdf

Reference Materials: DOTs / Projects

- Missouri's Experience with a Diverging Diamond Interchange: Lessons Learned

  http://library.modot.mo.gov/RDT/reports/UnNumbrd/or10021.pdf

- Missouri DOT Project Website – Springfield, I-44 & MO 13

  http://www.modot.mo.gov/springfield/major_projects/Greene/I-44andRoute13.html

- Missouri DOT Project Website – Kansas City, I-435 & Front Street

  http://www.435ddi.com/

Reference Materials: DOTs / Projects

- Missouri DOT Project Website – St. Louis, I-270 & Dorset

  http://www.modot.gov/stlouis/links/DivergingDiamondInterchange.htm

- Missouri DOT Staff Summary: DDI Results from the Right Transportation Solution Survey

  http://library.modot.mo.gov/RDT/reports/TRyy1013/orb10005.pdf

- What does a Diverging Diamond Look Like? MoDOT

  http://www.youtube.com/modotvideo#p/u/80/B5JtZMPTNAY

Reference Materials: DOTs / Projects

- New York Project Website – Rochester, I-590 & Winton Road

  https://www.nysdot.gov/regional-offices/region4/projects/590winton/diverging-diam

- Tennessee Project Website – City of Alcoa, US 129 Bypass and Bessemer Street

  http://www.cityofalcoa-tn.gov/city_departments/public_works_engineering_department/middlesettlements_road_bessemer_street_diverging_diamond_interchange_project

Reference Materials: DOTs / Projects

- Utah DOT Project Website – Sarasota Springs, I-15 & American Fork Main Street

  http://www.udot.utah.gov/pioneer/

  http://www.udot.utah.gov/pioneer/gallery2/main.php?g2_itemId=139

- Oregon: Diverging Diamond Interchanges: Oregon's Planned Applications Paper, Siromaskul & Warrick

  http://www.oregonite.org/2007D6/paper_review/D9_67_Siromaskul_paper.pdf

CASE STUDY: I-75 BOONE COUNTY, KY

2010 ASHE National Conference

June 10, 2010

Jake Stremmel, PE

HNTB

I-75 Boone County, Kentucky

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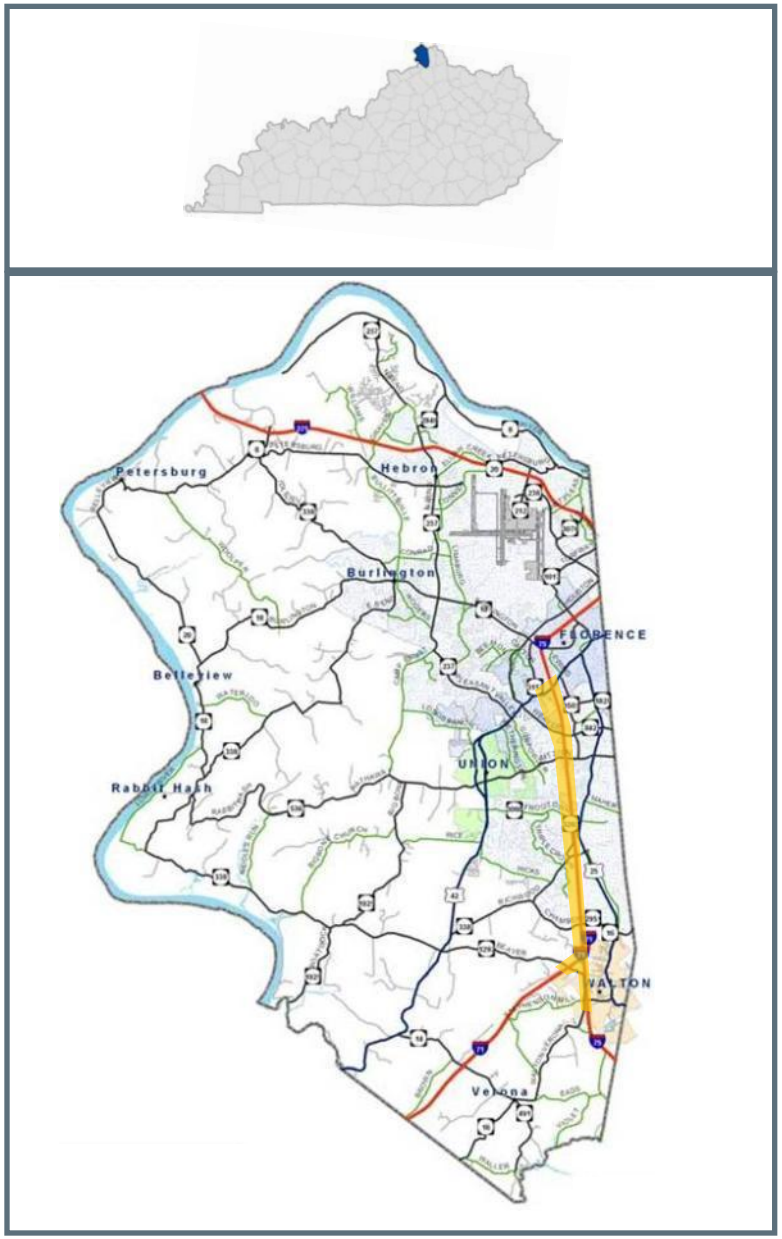
Boone County



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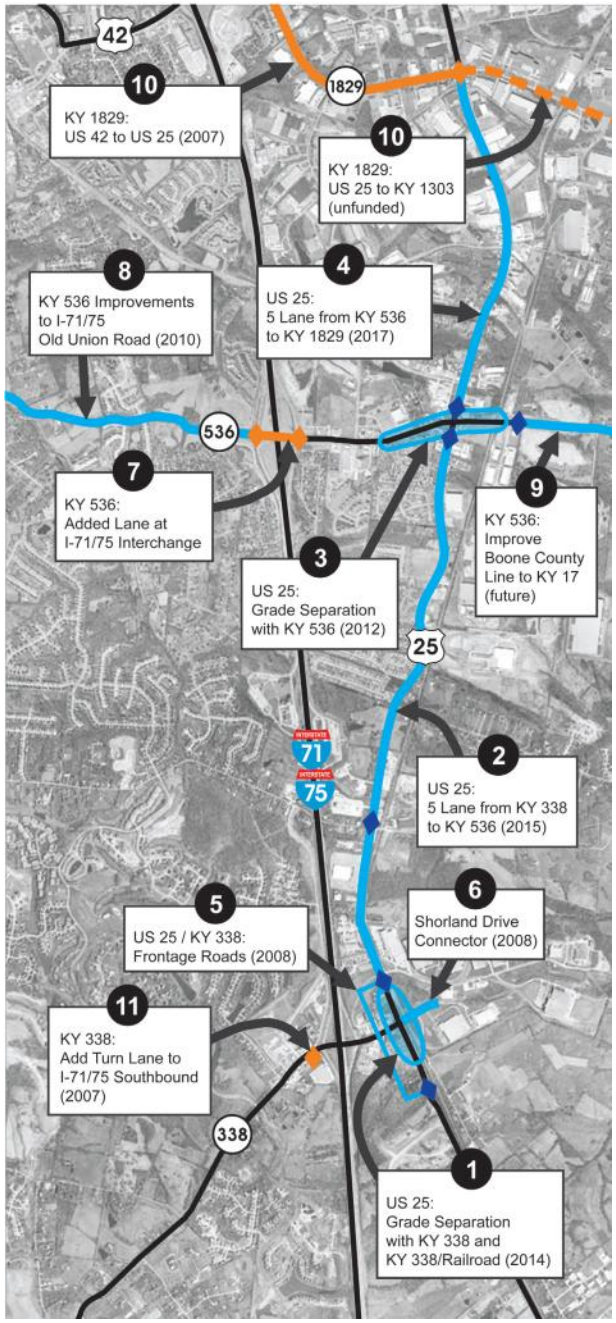
History

- Mt. Zion at I-75 interchange opened in 1994.
- Original traffic projections in 1994 on I-75 were 88,000 for year 2007.
- Within 5 years, traffic exceeded 88,000 ADT on I-75.
- 2006: 104,000 ADT on I-75
- 2006: 24,174 ADT on KY 536 (Mt. Zion Road)

Existing Geometry

Description	I-71/I-75 Mainline	KY 536 (Mt. Zion Road)
Functional Classification	Urban Interstate	Urban Arterial
Number of Lanes	3-4 in each direction	4
Posted Speed	70 mph	35-45 mph
Lane Width	12’	11-12’
Shoulder Width	14’-8”	6’-8’
Maximum Grade	2.75%	4.00%
Non-Passing Sight Distance	689’	537’

Study Area



Related Projects/Studies

Ongoing Construction/ Recently Completed

Future Construction

In Design

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Public Involvement

- The project team held 3 Stakeholder Advisory Council (SAC) Meetings consisting of:
  - Federal Highway Administration (FHWA)
  - Kentucky Transportation Cabinet (KYTC)
  - Northern Kentucky Area Planning Commission
  - Northern Kentucky Chamber of Commerce
  - Northern Kentucky Tri-County Economic Development Corporation
  - Ohio-Kentucky-Indiana Regional Council of Governments (OKI)
  - Transit Authority of Northern Kentucky (TANK)
  - Boone County Administration
  - Office of Judge Executive
  - Boone County Planning Commission
  - Boone County Public Works
  - City of Florence
  - City of Union
  - City of Walton
  - Norfolk Southern Corporation
  - Local Citizens and Business Leaders

Traffic - Existing Conditions

- 24 hour tube counts
- Turning movements at Peak Hours
- Existing signal timing
- Crash Data
- Evaluation using
  - HCS: capacity
  - Synchro: signal timing
  - Paramics: micro-simulation and visualization

Alternatives

No Build

1 – Additional Lanes to Existing Diamond

2 – Eastbound/Northbound Loop Ramp

3 – Eastbound/Northbound & Southbound/ Eastbound Loop Ramps

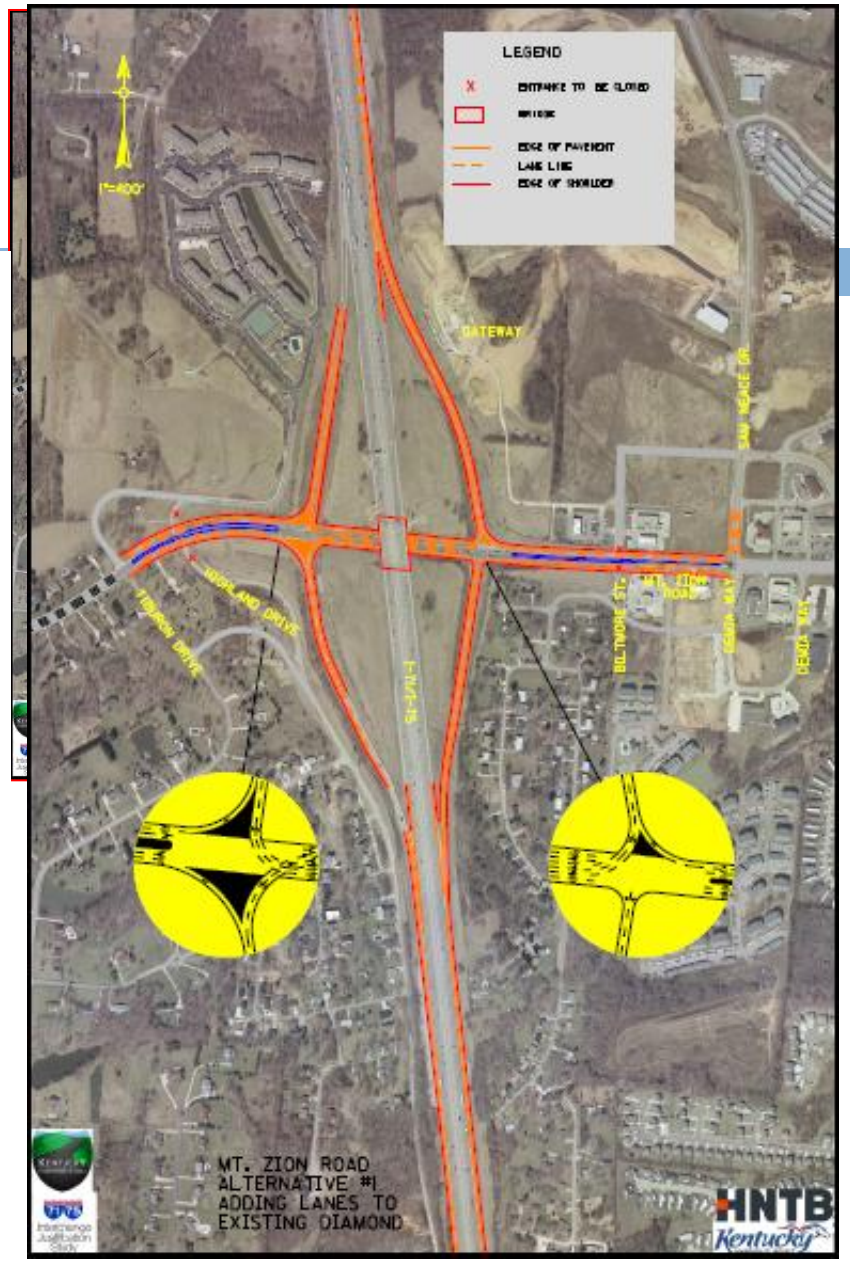
4 – Partial Cloverleaf

5 – Diverging Diamond Interchange (DDI)

6 – Single Point Urban Interchange (SPUI)

7 – Double Roundabout

8 – Directional Fly-Over



Evaluation Criteria

Financial Measures
Construction Costs
Right of Way Costs
Safety Benefits
Improvements to High Accident Locations
Acceleration
Conflict Points
Improves Incident Management
Levels of Service/ Mobility
Improves Travel Time (Capacity Constraints)
Freeway LOS & V/C
Local LOS & V/C
Suitable Local and Interstate Truck Access

Design
Efficient with Heavy Truck Volumes
Meets Current Design Standards
Provides for Pedestrians
Socioeconomic - Environmental
Relocations
Access to/from Community Facilities
Access to/from Businesses
Natural Areas
Noise/Air Quality
Access to Public Transportation

Equity (Environmental Justice)
Equitable Distribution of Benefits
Equitable Distribution of Impacts
Implementation
Schedule
Maintain Traffic on KY 536
Maintain Traffic on I-75

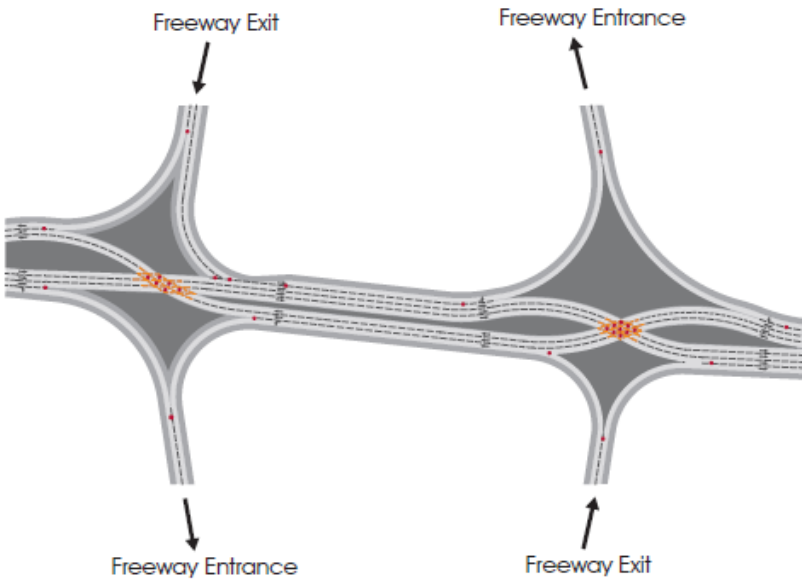
Traffic Comparison

- LOS C = Desired
- LOS D = Minimum Acceptable
- Targeting a V/C< 1.0

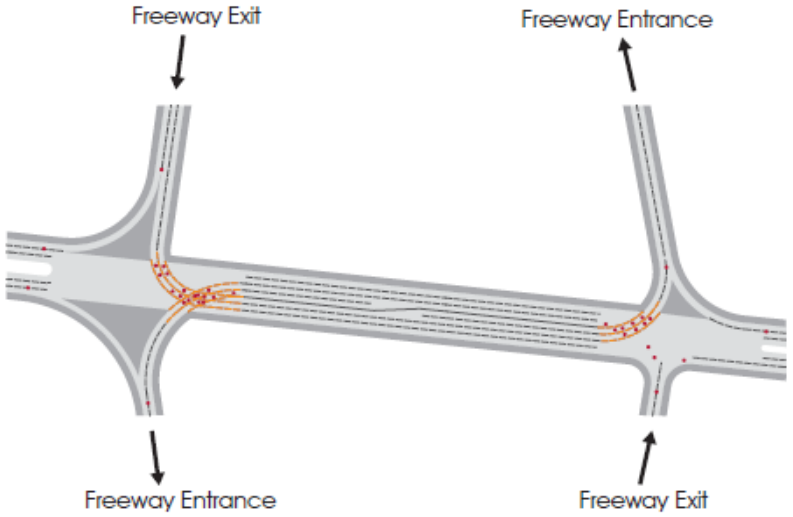
		Traditional Widening (9 lanes)		Diverging Diamond Interchange (8 lanes)	
		West	East	West	East
Mt. Zion	AM	C	B	B	B
Mt. Zion	PM	C	B	B	B

Safety Comparison

Diverging Diamond - 29 Conflict Points



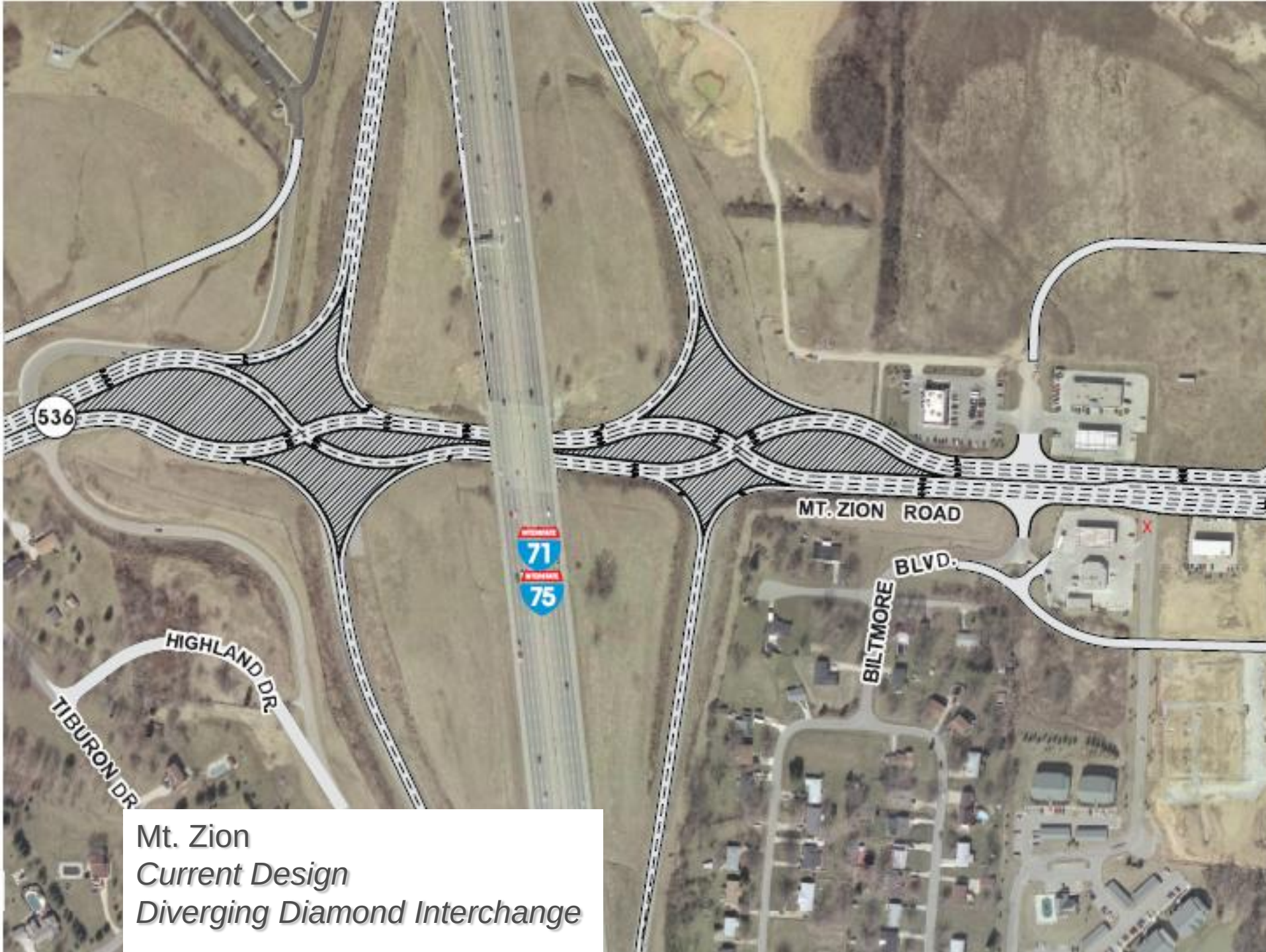
Traditional Widening – 36 Conflict Points



Construction Cost

- Traditional Widening
  - Construction = $23M
  - ROW = $2.9M
  - Utilities = $1.8M
- Diverging Diamond
  - Construction = $16M
  - ROW = $2.9M
  - Utilities = $1.8M

Cost Difference = $7M



Mt. Zion
Current Design
Diverging Diamond Interchange

Design Lessons Learned

- DDI's typically work better than other options (SPUIS, tight diamonds) when traffic is unbalanced. In our case, a heavy left movement makes the DDI a better solution.
- Minimum 50 degree intersection skew angle
- 600' minimum storage between ramps.
- Left turn lane capacity is roughly 2x that of a normal left turn lane.
- Considered safer for pedestrians.

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CASE STUDY – IR 480/TIEDEMAN RD.

2010 ASHE National Conference

June 10, 2010

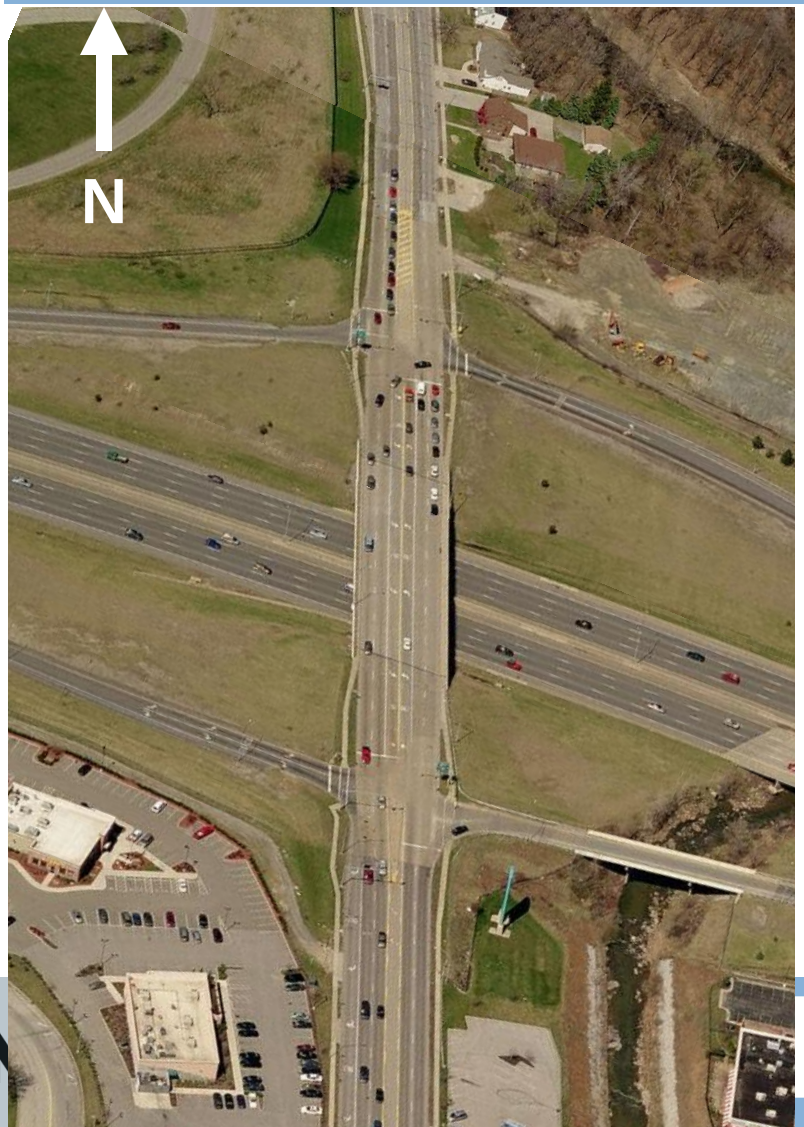
Jim Shea

HNTB

Project Location/Background

- Brooklyn, Ohio
- I-480 original construction 1985
- SAFETEA-LU earmark received for engineering
- City led project, ODOT review
- Plain Dealer, Key Bank, Hugo Boss, American Greetings, hotels, restaurants

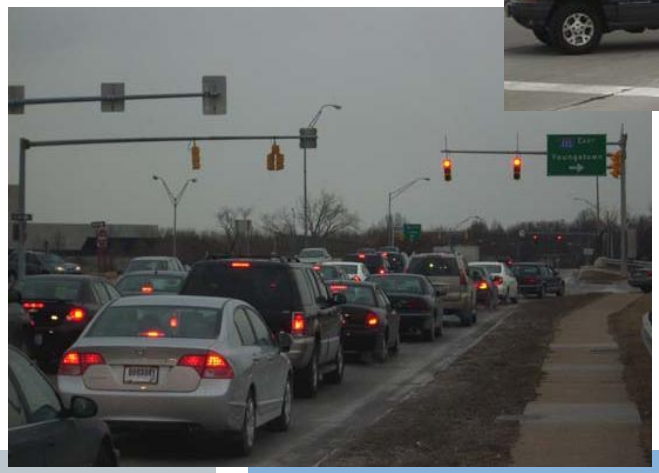
Existing Conditions



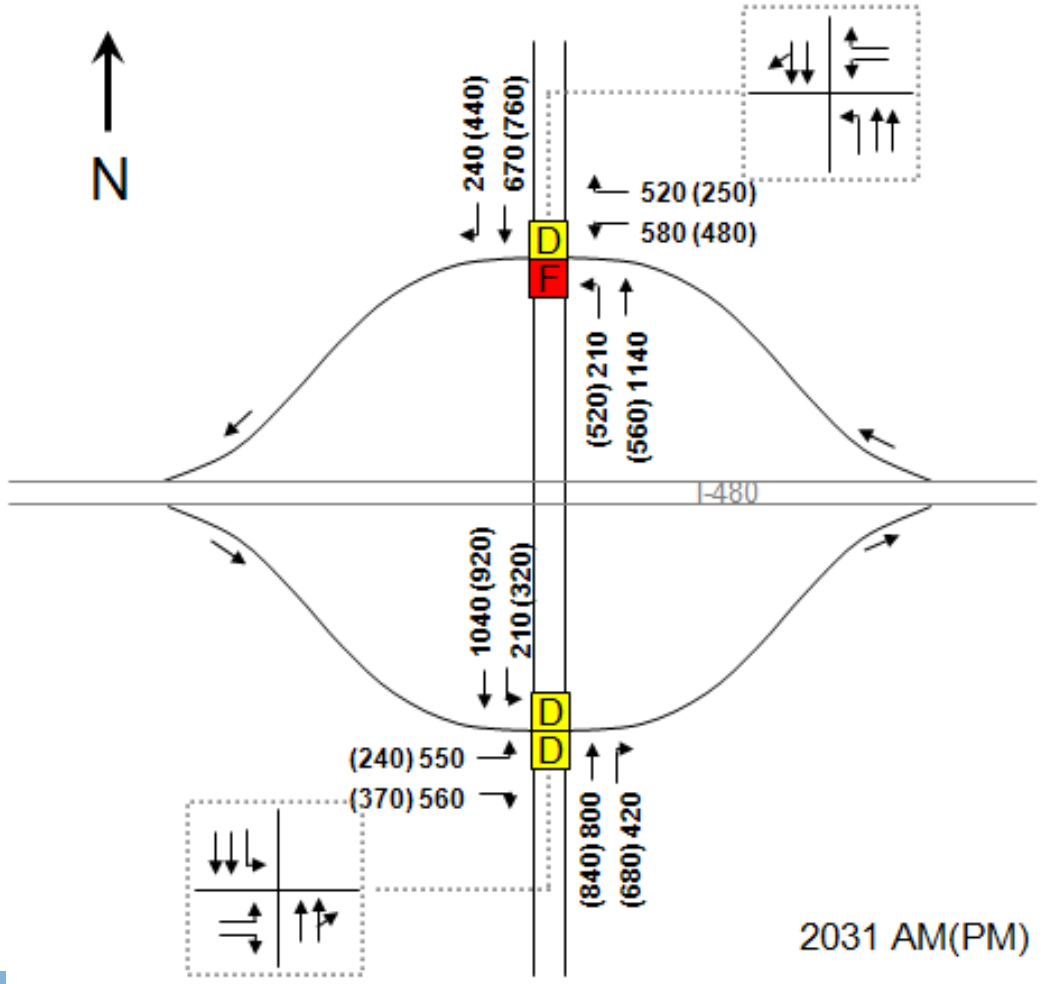
- 5-lane wide bridge, restriped to 6-lanes
- Excessive left turn volumes onto I-480
- Peak period congestion
- Traffic back up on arterial and mainline freeway

Project Goals

- Improve traffic flow and level of service
- Improve safety



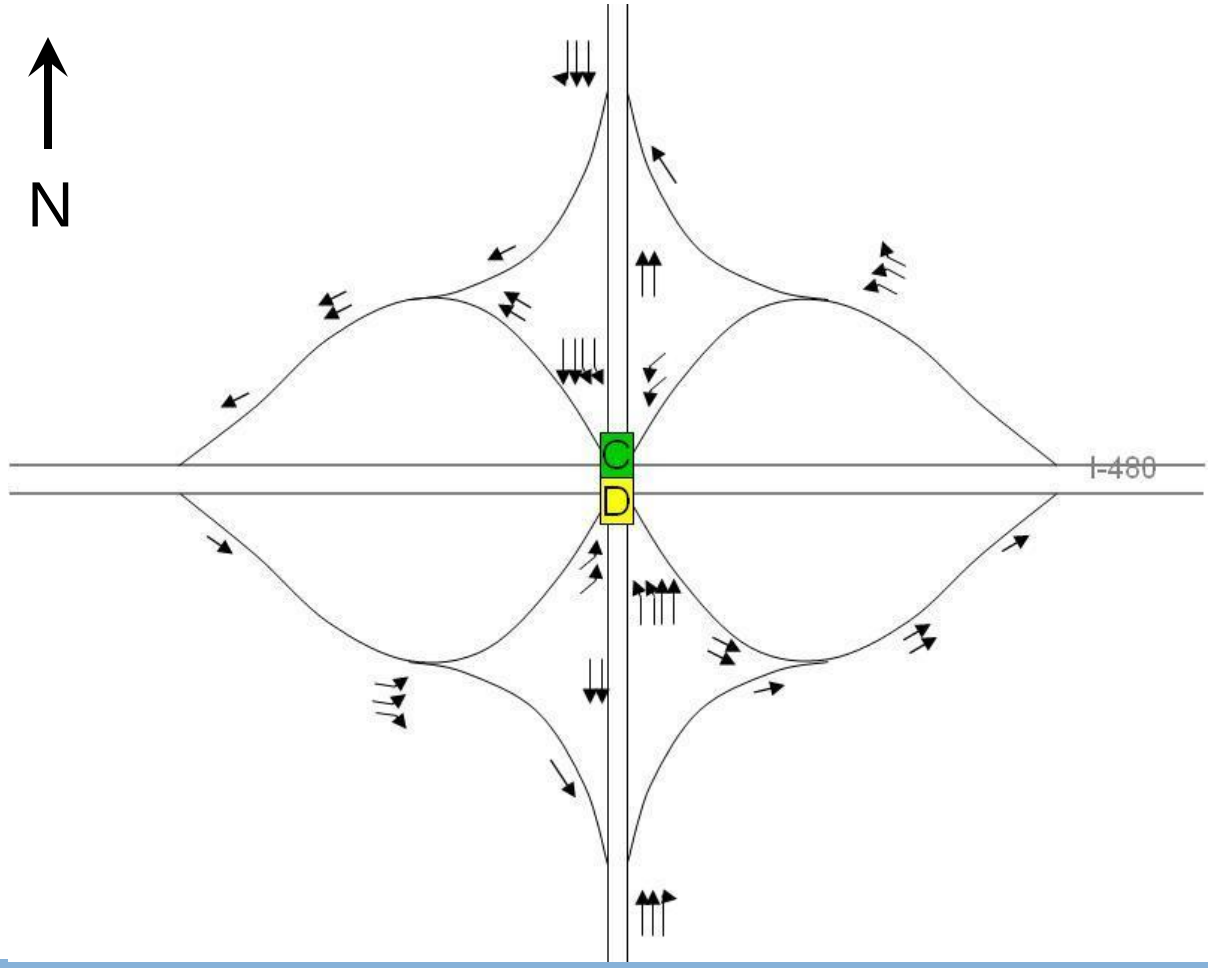
Future Traffic Volumes



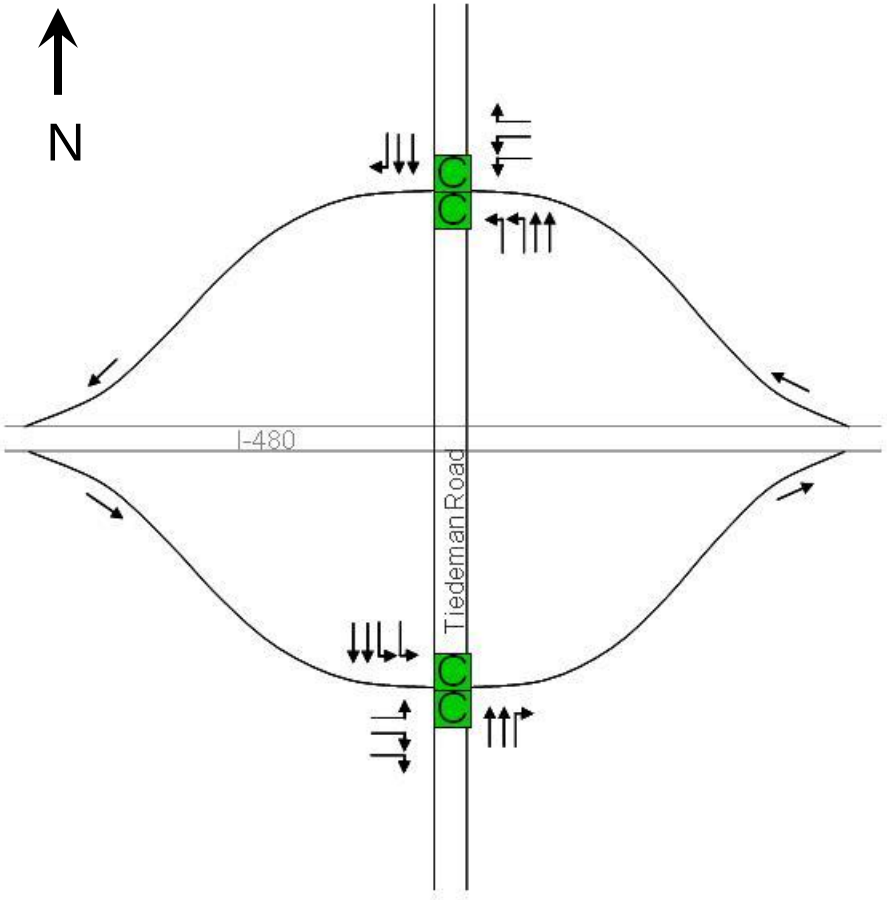
Alternatives Examined

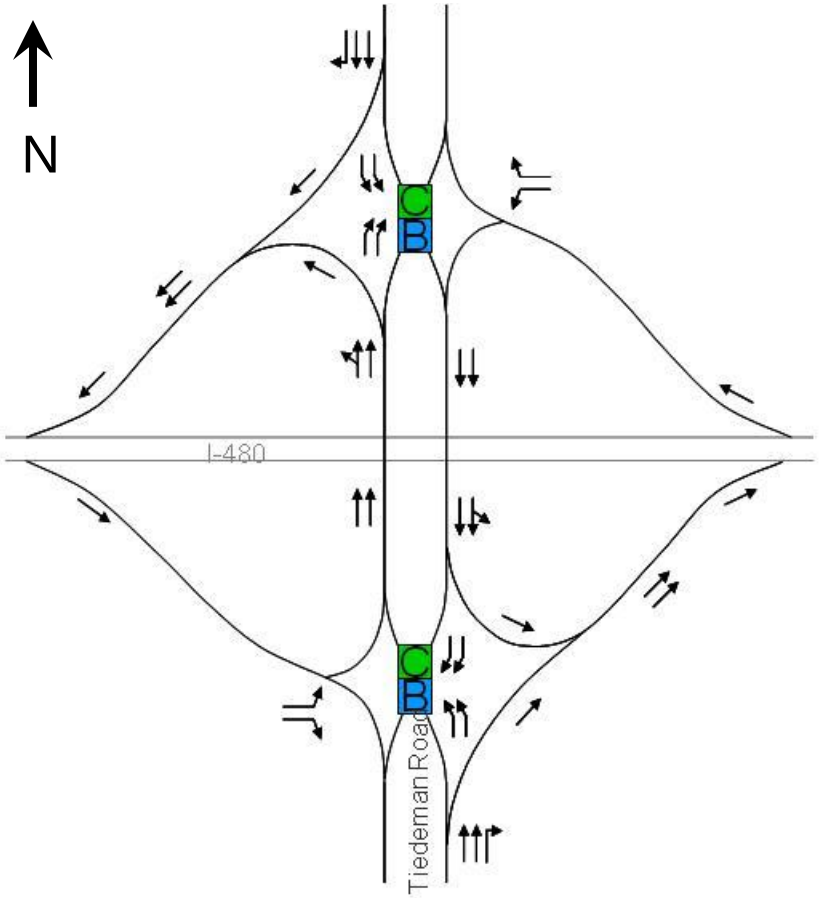
- Single Point Urban Interchange (SPUI)
- **Upgraded Diamond**
- **Diverging Diamond**

SPUI



Upgraded Diamond vs. DDI





Upgraded vs. Diverging Diamond

Upgraded

- Bridge widening
- 2-lane entrance ramps
- 3-lane exit ramps
- LOS C
- ~$13M

DDI

- Maintains bridge width
- 2-lane entrance ramps
- 2-lane exit ramps
- LOS C and B
- ~$8M

Why the DDI?

- Increased safety
  - Less conflict points
- Better traffic operation
- Cheaper
  - Bridge maintained
  - Less ramp lanes

Preliminary DDI Layout

Questions